Using a mechanistic model for evaluating ammonia emissions abatement techniques after organic fertilization

Utilisation d'un modèle mécaniste pour évaluer des techniques de réduction des émissions d'ammoniac après fertilisation organique.

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Abstract

A mechanistic model of ammonia volatilization after liquid effluent spreading was used to investigate the efficiency of ammonia loss abatement techniques and strategies under a wide range of agricultural and environmental conditions. It proved to be a useful tool to compare these techniques, and to evaluate the conditions where they are the most efficient. It should thus be used further to help the farmers to choose between the practical strategies and methods aiming at reducing ammonia emissions after land disposal.

Keywords : Ammonia volatilization, Mechanistic modeling, Organic manure, Abatement techniques

Résumé

La réduction des émissions d'ammoniac après l'application d'effluents d'élevage ou urbains permettrait de limiter les pertes d'azote issues de l'activité agricole et les impacts environnementaux liés à l'augmentation de la concentration atmosphérique en ammoniac. Plusieurs approches se sont révélées efficaces pour limiter les pertes d'azote par les sols cultivés : elles incluent les modifications des propriétés des effluents, le travail du sol et une meilleure gestion des épandages. Cependant, les interactions fortes avec le climat, le sol et le lisier rendent difficile toute extrapolation. Nous avons développé un modèle mécaniste pour simuler la volatilisation à un pas de temps horaire, dans différentes conditions de sol, lisier et climat. Il a été utilisé pour tester ce type de techniques. En premier lieu, nous avons montré que les résultats des simulations avec le modèle concordaient avec des résultats publiés d'expérimentations au champ : l'amplitude de la réduction est bien reproduite pour l'acidification ou la dilution de l'effluent, et pour l'incorporation ou l'irrigation après l'apport. Ensuite, grâce à des simulations appropriées, le modèle a servi à évaluer et comparer l'efficacité de quelques techniques dans une large gamme de conditions agricoles et environnementales : par exemple, l'acidification n'est réellement efficace que sur une gamme limitée de pH, qui dépend en outre de la température ; l'irrigation est d'autant moins efficace que le sol est humide. Ce modèle mécaniste est donc un outil utile pour améliorer la gestion des ressources agricoles et naturelles, et pour la protection de l'environnement. Il devrait être utilisé dorénavant pour proposer aux agriculteurs des stratégies et des méthodes pratiques visant à réduire les émissions d'ammoniac lors de la valorisation agricole des effluents.

Mots-clés : volatilisation d'ammoniac, modélisation mécaniste, amendement organique.

1. Introduction

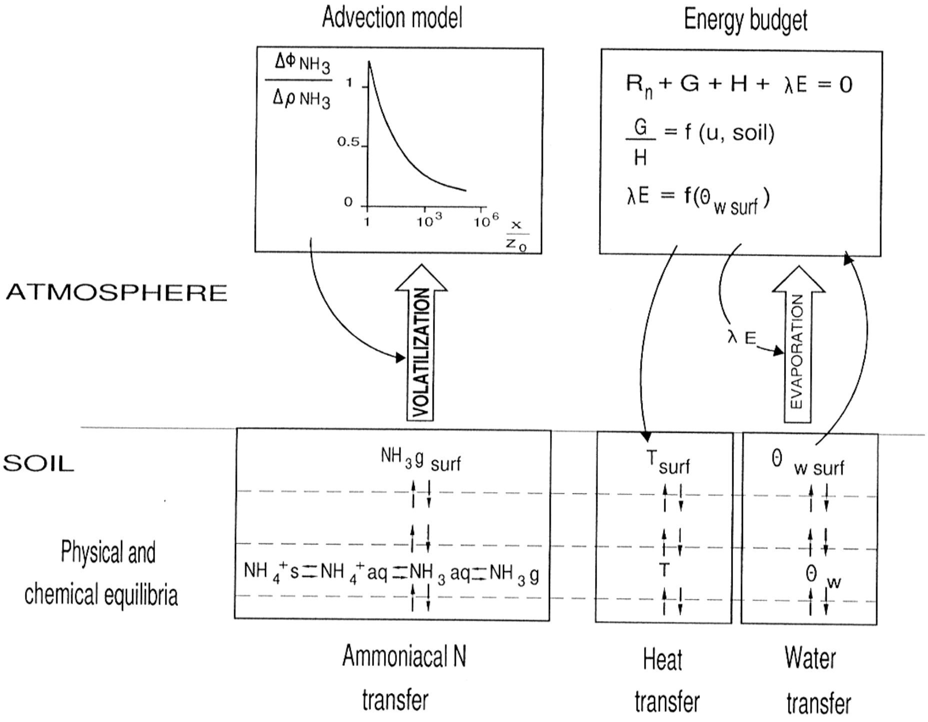
Reducing ammonia emissions after farm or urban effluents application would minimize the great gaseous nitrogen loss from agriculture. Indeed ammonia emissions following slurry application account for almost one third of the European source of atmospheric ammonia (Buijsman *et al.*, 1987; ECETOC, 1994). In contrast to the other agricultural sources (animal housing, manure storage, grazed pasture), their emissions are time limited (several days to several weeks), intense just after application (several tens of kg N-NH_3 ha^{-1} j^{-1}). Furthermore, they vary in a wide range (0-100% of ammoniacal N applied), depending on many features of the soil, climate and slurry (Jarvis and Pain, 1990; Génermont, 1996). They represent then great nitrogen losses for the agro-systems, which is a matter of considerable economical and environmental importance, but difficult to evaluate and to reduce.

Several techniques aim at reducing ammonia losses from cultivated soils: they include slurry properties modifications, soil management and better slurry application management (Hauck, 1983; Frost, 1994; Sommer and Hutchings, 1995). But ammonia volatilization is a complex process, involving many physical mechanisms, and the reducing techniques have strong interactions with the climatic, soil and slurry conditions (Jarvis and Pain, 1990). Their efficiency is thus difficult to extrapolate to other conditions. This paper aims at showing how a mechanistic volatilization model could help evaluating and comparing such techniques in a wide range of agronomic and environmental conditions. It is finally used to propose recommendations to farmers.

2. Materials and methods

2.1. Mechanistic model

The mechanistic model is derived from those of Rachhpal-Singh and Nye (1986) and van der Molen *et al.* (1990). It simulates volatilization at a hourly interval under various soil, slurry, climate conditions (Génermont and Cellier, 1997). It accounts for the main mechanisms implied in ammonia volatilization, water and ammoniacal N transfers, and equilibria in the topsoil and between the soil and the atmosphere (figure 1).



With:	E	soil evaporation	x	abscise in wind direction
	G	soil heat flux	z_0	roughness length
	H	atmospheric sensible heat flux	θ_V	soil water content
	R_n	soil surface net radiation	θ_{Vsurf}	soil surface water content
	T_{sol}	soil temperature	λ	latent heat of vaporization
	T_{surf}	soil surface temperature	ρ_{NH_3}	atmospheric ammonia density
	u	wind speed	Φ_{NH_3}	ammonia flux

Figure 1
Diagram of the volatilization model

- the relative proportions of ammonia and ammonium are calculated from the acid base equilibrium constant (1); the equilibrium between gaseous and solute ammonia is obtained from Henry's law (Beutier and Renon, 1978); adsorption by clays and organic matter of the soil is described using a Freundlich isotherm (Rachhpal-Singh and Nye, 1984).

- (4) water transfer is described by Darcy’s law, generalized to the unsaturated zone; soil hydraulic characteristics are deduced from pedotransfer functions (Clapp and Hornberger, 1978); ammoniacal N transfer is described by a convection-diffusion scheme (2) (Bear, 1972);

- volatilization is calculated with an advection model (3) (Itier and Perrier, 1976); it allows to account for local advection and makes the model suitable for field scale applications.

- evaporation and surface temperature are calculated by solving the energy balance of the soil surface (6) using Noilhan and Planton (1989) and Cellier *et al.* (1996) parameterizations.

The model uses readily available input data, including soil and slurry characteristics, hourly meteorological data, and technical informations. It was tested under agricultural conditions and the simulation was satisfactory for the global amount and the hourly variations.

Although pH is the most sensitive factor of the model, pH variations were ignored, and pH was taken constant for all simulations. Biophysical processes such as ammonification, nitrification, *etc*. were neglected (Génermont *et al*., 1997).

2.2. Reference situation

The reference data used for the simulations came from an experiment carried out at the INRA experimental station of Le Rheu, near Rennes (Brittany, France). 133 m^3 ha^{-1} of cattle slurry for a total ammoniacal nitrogen supply of 114 kg N ha^{-1} were applied on March 16, 1994 (day of year 75) over a 1.7 ha field, on a bare slightly acid (pH = 6.6) loam soil with water content at field capacity. The meteorological data were measured at the experimental site. For more details, see Génermont (1996). Simulations were performed for a 10 day period which allows to account for almost the total losses in most cases.

2.3. Simulations

Simulations were performed by changing one single factor at a time by adding a coefficient to the reference value or by multiplying it. The imposed range of variation was chosen in accordance with literature recommendations and/or with reasonable agricultural practices. We calculated the cumulative losses for different times after spreading. The response of the model to a change in one factor was analyzed by using the ratio of the cumulative losses with this factor to the loss in the reference simulation. When quoted in the text, the reduction always refers to the loss obtained as % of the loss of the reference simulation.

3. Slurry properties modification

3.1. Acidification

Initial slurry pH are generally rather basic (7-8.5), which favors ammonia volatilization. Slurry acidification is thus often recognized as an efficient mean to reduce volatilization.

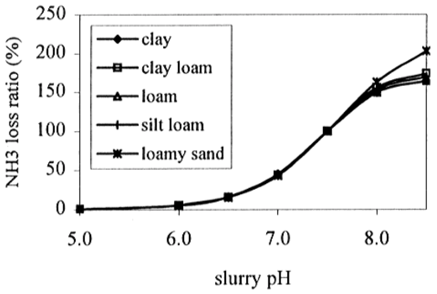


Figure 2
Simulated effect of slurry acidification on loss, for different soil types

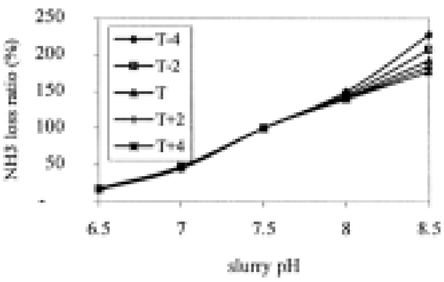


Figure 3
Simulated effect of slurry acidification on loss, for different temperatures

Simulations were performed for different soil types (Fig.2) and climatic conditions (Fig.3). They show that acidification was more efficient for a sandy soil (Fig.2), for which however losses were small (14-17%) compared to the other soils. It was also more efficient for alkalin slurries under cold conditions (Fig.3).

Simulations are in agreement with published results of field experiments. Volatilization calculated with pH 6 (resp. 6.5) was 12% (resp. 15%) of that with pH 7 (resp. 7.5) which was close to the observed reduction to 20% for a drop in pH from 7 to 6 by Stevens *et al*. (1989).

Jarvis and Pain (1990) recommended to bring the slurry pH down to 6 or 5. But bringing it to 5 is not worthy compared to bringing it down to 6 (Fig.2), because losses were almost zero for both pH. This is an interesting result, as acidification becomes more costly when pH decreases: 1 pH unit decrease needs 10 times more acidifying substance than the one before.

These results give an idea of the potential for lowering ammonia loss by acidification. However the effect of acidifying different slurries to similar pH values may be variable because emissions are also related to the slurry buffering capacity (Husted *et al.*, 1991).

3.2. Dilution

Stevens *et al.* (1992) observed that diluting the slurry decreased ammonia volatilization (*Table 1*). By simulating the same treatments, the model calculated smaller reduction in ammonia loss (*Table 1*), which may be linked to the differences in soil, slurry and climate.

	Stevens *et al*., 1992	Model simulations	Comparison with washing	Model simulations
Dilution (% by volume of slurry)	Measured loss (% of loss without dilution)	Calculated loss (% of loss without dilution)	Corresponding volumes of water for washing	Calculated loss (% of loss without washing)
0	100%	100%	0.0 mm	100%
40	83%	88%	5.4 mm	63%
100	50%	73%	13.4 mm	31%
140	39%	63%	18.8 mm	24%

Table 1
Comparing simulations of slurry dilution using the model to the results of Stevens et al. (1992) and to the effect of washing after application, using the same volumes of water (see below)

4. Application and post-application control techniques

4.1. Soil cultivation

Many publications refers to the influence of soil management on ammonia losses. The effect of the depth of incorporation was often studied. As slurry is incorporated into the soil, it is much less in contact with the atmosphere and the resistance to ammonia transport upward in the soil is large. As a consequence, several means of deep placement of ammoniacal N such as direct injections or incorporations just after application were proposed to the farmers, in order to reduce volatilization and to preserve the slurry fertilizing value. But observations in field conditions also evidenced that cultivation after application only resulted in the deep placement of a fraction of the slurry, the other fraction remaining at the surface. Simulations were made to evaluate the effect of partial incorporation by changing the placement of the slurry in the soil sub-model.

Simulations showed that the efficiency of the depth of incorporation highly depended on the proportion of slurry incorporated (Fig.4). Small depths were only efficient when at least 80% or almost all the slurry was incorporated (Fig.4 et 5), which corresponds to harrowing. When plowing with a rotavator, more slurry remains at the soil surface, and slurry should be incorporated at more than 10 cm deep in order to efficiently reduce ammonia losses.

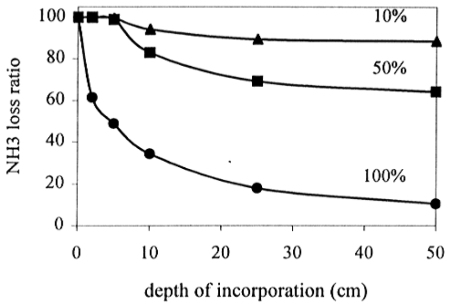


Figure 4
Effect of the depth of incorporation on loss,for three proportions of slurry incorporated

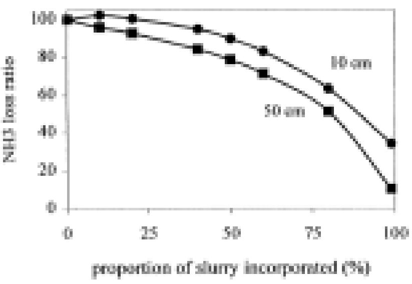


Figure 5
Effect of the proportion of the slurry incorporated on loss, for two incorporation depths

4.2. Washing

Some authors also recommend to bring water after slurry, as it enhances ammoniacal N infiltration into the soil and dilutes ammoniacal N remaining at the soil surface.

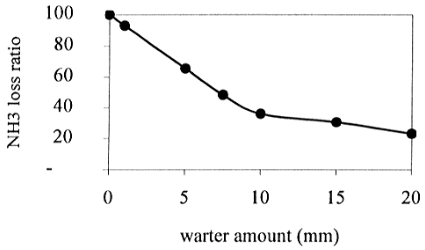


Figure 6
Simulated effect of washing after slurry application on ammonia volatilization

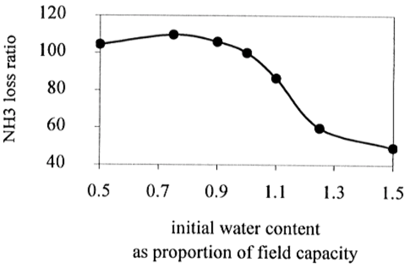


Figure 7
Effect of washing as a function of the soil initial water content

Simulations confirmed that losses were efficiently reduced, and showed that the optimal water amount is around 10 mm: with less water, losses were less reduced, but for greater amounts, reduction did not increase (Fig.6). Simulating a 10 mm irrigation immediately after slurry application, the influence on ammonia volatilization (36%) was similar to that measured by Moal *et al*. (1995) (32%), but was much less than that measured by Klarensbeek and Bruins (1991) (67%). This discrepancy could be explained by interactions with environmental conditions. For example, simulations with various initial soil water contents showed that washing was more efficient in this case for soils with high initial water contents. It is then interesting to compare the effect of either diluting the slurry before application, or bringing the same amount of water after the slurry has been spread. Results of simulations were reported on *Table 1*: washing after application appeared to be highly more efficient than slurry dilution before application. Then farmers, knowing this kind of result, will be able to choose which strategy to adopt, as a function of their own equipment and agronomic constraints (dilution apparatus, time for application, trafficability, *etc*.).

4.3. Timing of agricultural techniques

Simulating plowing or washing at different dates after spreading evidenced that their timing is very important (Fig.8). In some cases, a delay of only several hours might ruin the effect of soil plowing. This is due to the fact that the rate of ammonia volatilization is directly related to the concentration of ammonia in solution: fluxes are high at the beginning of the volatilization period (1-2 days) and then decrease exponentially owing to the decrease in available ammoniacal N. The loss reduction was approximately exponentially inversely related to the delay between slurry application and plowing or washing. This confirmed and enlargeed the results found by Sommer (1992): losses when the soil was harrowed just after application were 33% of those when it was harrowed only 8 hours after. As a consequence, the post-application control techniques must be brought into operation as quickly as possible if the farmer want them to be really effective, and even sometimes worthy.

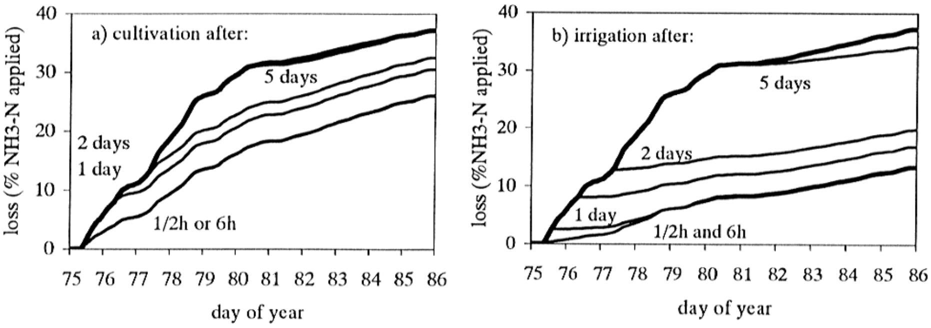


Figure 8
Simulated cumulative loss of ammonia volatilization after slurry spreading followed by a) incorporation or b) washing at different dates

5. Slurry management and agronomic strategies

5.1. Slurry application timing

National and regional legislations recommend or impose periods in the year for land disposal of slurry, mainly in order to reduce nitrate leaching. The choice of these periods is of great importance, as ammonia losses are weather-dependent. Generally, measures are set up so that slurry is spread under wet or/and cold climatic conditions, where ammonia losses are known to be small. The two factors that will be mainly affected by applying slurry at different dates are temperature and soil water content. Volatilization is high under warm conditions (Fig.9). The effect of soil water content is less clear: on the one hand, on a wet soil, the slurry ammoniacal N is diluted, and emissions should be reduced; but on the other hand, infiltration is reduced, which should increase emissions. Simulations performed to investigate the effect of the initial soil water content on volatilization showed that losses were reduced for dry soils and even more for wet soils (Fig.10): in the first case, infiltration was the dominating factor influencing ammonia volatilization, and in the second case, ammoniacal N dilution was prevailing. Ammonia losses were really efficiently reduced for high initial water contents, compared to the soil water content at field capacity. But in practice, this conflicts with the need for good trafficability of the soil for spreading and even after for incorporation. As a consequence, the choice should rather be oriented by the temperature considerations, and not by the soil water content at the time of spreading. Unfortunately the timing of slurry applications then conflicts with the desire for good growing conditions to promote the efficient utilization of the slurry nutrients.

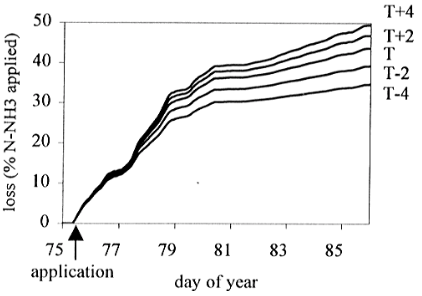


Figure 9

Using the model for studying the effect of temperature on ammonia volatilization

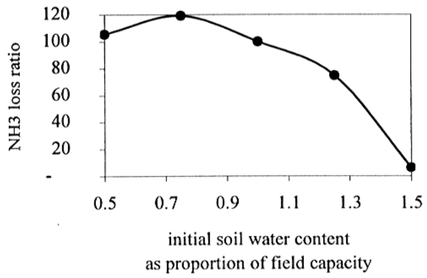


Figure 10

Using the model for studying the effect of initial soil water content on volatilization

The choice of the time in the day for spreading has also been discussed by Klarenbeek and Bruins (1991). Simulations showed that, losses during the first day were significantly reduced (≈ 60%) when slurry was applied during the night (9-12 p.m.). But the effect was very small when accounting for the total loss over the whole volatilization event (only 1-3 %).

5.2. Slurry application at the farm scale

Furthermore, the technical and strategic choices will have to be taken at the farm scale. The results of simulations for soils with various textures showed that total loss could highly differ. For example, losses for a sandy soil were 14-24% of those of loamy and/or silty soils, with the same pH. For farms with heterogeneous soils (texture, pH, cation exchange capacity, *etc.*), this implies that abatement techniques must be preferentially applied to soils with the higher potential for volatilization, than to the others.

6. Conclusion

This presentation showed how using a model could help evaluating and improving means and strategies used to reduce the N losses through ammonia volatilization after organic fertilization. By integrating explicitly factors related to climate, soil and slurry, this mechanistic model helps investigating more thoroughly the efficiency of such techniques. It therefore is a useful tool for improving the management of the agricultural and natural resources and for the protection of the environment.

Furthermore, the efficiency of such techniques strongly depends on the emission conditions. To justify the cost of advanced slurry pretreatment and application equipment for a farmer, they should really be efficient under all environmental conditions prevailing in the area. The further intensive use of this model would allow to more precisely identify for which type of agronomical, pedological and climatic conditions which kind of abatement technique will be the most efficient, and the right equipment to invest in. By coupling it with an economical model, it would then allow to stand out the cost efficiency of such measures. For example, slurry properties modifications have sometimes been recognized to be expensive compared to their efficiency. The combination of both models will help determining if they are to be efficient when it is not possible to cultivate the soil, on grass land or non-tillage systems for example.

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